

Review

# Phase Change Materials (PCMs) and Their Optimum Position in Building Walls

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Received: 2 December 2019; Accepted: 14 January 2020; Published: 11 February 2020



**Abstract:** More than half of the energy consumption in buildings is utilized for the heating and/or cooling of the indoor environment. The building envelope plays a key role in controlling the effects of external weather and, therefore, is linked with many passive design strategies. Thermal energy storage (TES) and phase change materials (PCMs) are efficient techniques, which can store a high density of thermal energy. The PCMs attract many researchers to implement them in the components of buildings for thermal management. In building walls, they were implemented in different positions and have achieved different results. This paper aims to review the related literature that examines PCMs' application in different positions within the building walls to locate their optimum position and the influential parameters. It was found that the optimum positions of PCMs are highly dependent on performing a daily complete melting/freezing cycle to be ready for the following day. Many parameters can influence this, including climate and weather conditions and the application target, PCMs' melting temperature and heat of fusion, PCMs' amount, the thermal properties of the wall's materials, a mechanical heating/cooling or free-running indoor environment, and wall orientation. An optimization process using the simulation tools is suggested so that the optimum position of the PCMs can be located.

**Keywords:** Thermal energy storage (TES); Phase Change Materials (PCMs); PCMs application in walls; PCMs optimum positions

## 1. Introduction

Originally, buildings were commonly constructed using local materials. This helped to protect them from local climate conditions and respond to the ambient environment [1]. Traditional buildings were more climate-responsible as they were built to ensure the best control and utilization of climate factors for the inhabitants' comfort based on the available materials and technologies. Therefore, they showed a better indoor environment and less energy consumption [2,3]. During the industrial revolution, with people migrating to urban areas, which caused overcrowding, the focus of the building construction sector changed from climatic requirements to economical consideration. This resulted in a high dependency on mechanical systems to achieve thermal comfort. However, due to the energy crisis and the negative effects associated with massive energy use, such as climate change, global warming, and greenhouse gas emissions, humans should reduce energy consumption for the sustainability of the planet [1]. Buildings are responsible for 40% of global energy consumption, with as much as 60% of this energy being used for heating and cooling [4]. The building envelope plays a major role in the heat gains and/or losses in buildings [5]. Therefore, buildings provide a great opportunity through their envelope to minimize this high energy consumption by introducing more promising solutions, like passive design strategies.

Thermal energy storage (TES), particularly phase change materials (PCMs) are useful sustainable passive technologies that can be used in the building fabric to improve heat exchange and energy

efficiency and minimize energy consumption [6]. They can store a high density of thermal energy with slighter temperature change [7]. The favourability of using PCMs lies in the ability of a thin layer of PCMs to store a large amount of heat. Many researchers implemented them in buildings to improve the thermal performance of building materials and minimize energy consumption. Previous studies extensively reviewed TES and PCMs in terms of materials' development, type, properties, performance, methods of testing, and methods of application [8–17].

It was observed that some works examined the application of PCMs in different positions within the building walls (i.e., two positions—internally and externally—and up to 16 different positions) looking for the optimum position, which guarantees the best performance. However, different results were achieved. For instance, the optimum position was achieved in the internal layer of the wall [18–20], in the external layer of the wall [21,22] or within the wall section (i.e., in the middle, close to internal surface or close to external surface) [7,23–27]. The current work, therefore, aims at reviewing the previously conducted studies, which examined PCMs in different positions within the buildings' walls to locate the optimum position of PCMs, and identify the parameters that have an impact on achieving a variety of PCMs' optimum position in these studies. This work starts with a brief introduction on TES, then PCMs and their types, properties, advantages, requirements for their application, and methods of integration into buildings. After that, it addresses the application of PCMs in buildings' walls, focusing mainly on reviewing and analysing previous works that have examined PCMs in different positions to find the best performance and the optimum position. The methodologies of these works were studied and reviewed in detail to identify the involved parameters and understand their influence on PCMs performance.

## 2. Thermal Energy Storage (TES)

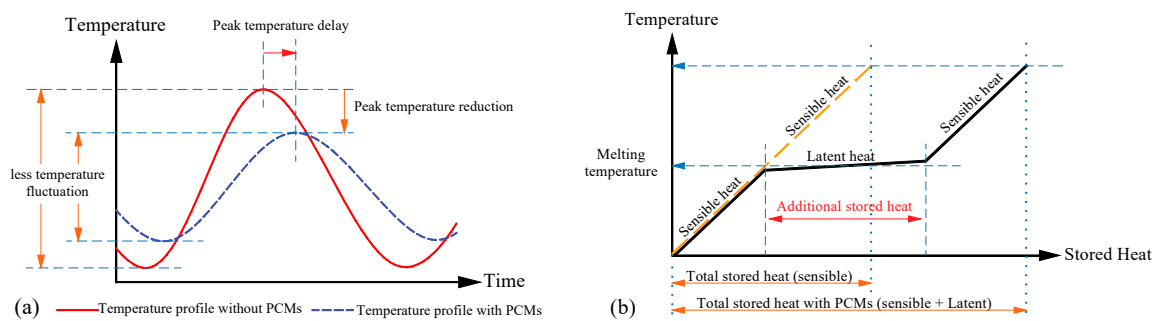
Thermal energy storage (TES) is basically the storing of the available thermal energy in order to reuse it during its shortage. The most significant value of TES is that it can solve the mismatch between the supply and demand of energy [28]. For instance, with TES, solar energy during the day-time can be stored to be used for heating the cold night-time, while the coolness of night-time can be used for cooling the warm day-time [29]. Furthermore, it is possible to store the heat of the warm summer months for heating in winter, and the coolness of the winter for cooling in summer. This is known as seasonal TES, which can help in meeting the energy needs caused by the seasonal temperature fluctuations [28]. Water and ice are often regarded as the favoured storage mediums for heating and cooling, respectively. TES can improve the heat exchange and energy efficiency of buildings [6] and can help in reducing fuel consumption through the effective use of equipment and systems that utilize thermal energy. Furthermore, the wasted low-cost energy, where its time of generation differs from the thermal demand period, such as passive and active solar heating and the internal heat produced by occupants, lighting, cooking, and appliances, can be utilized through TES [14]. Moreover, low-cost energy can be purchased during off-peak periods and stored for high-rate periods. Besides, TES reduces the peaks in energy demand, which, in turn, reduces its associated cost [14].

TES capture (charge), store, and reuse (discharge) the thermal energy. Energy storage in materials has three types, known as sensible heat, latent heat, and thermochemical [4,30]. The best known types for TES are sensible heat (i.e., storage by causing a temperature rise) and latent heat (i.e., storage by causing a phase change) [28]. However, the latter is preferable [14].

## 3. Phase Change Materials (PCMS)

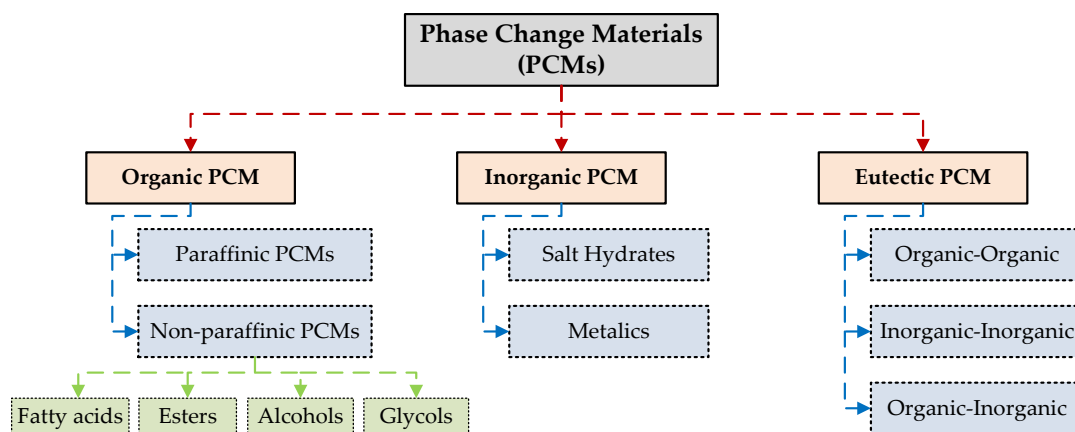
PCMs are the types of TES materials in which the latent heat is absorbed or released during the material's phase change. They can help in regulating the ambient temperature within a specific range close to their transition temperature. When the ambient temperature increases more than the PCMs' melting temperature, the chemical bonds in the material break up causing the material to absorbing the additional heat, while its state changes from solid to liquid. On the other hand, once the temperature drops below the PCMs' freezing temperature, the material discharges the energy and,

therefore, changes back to the solid-state [16]. If the material's phase transition temperatures (i.e., the melting and freezing temperatures) match with the required comfort temperature in buildings, it can help to maintain the indoor thermal environment within comfortable conditions and reduces the total hours of thermal discomfort by absorbing the extra heat [4] and, thus, reducing the heating and/or cooling loads. Figure 1a illustrates how PCMs can improve a building's indoor environment by reducing indoor temperature peaks and fluctuation. Furthermore, the favourability of using PCMs lies in the ability of a thin layer of PCMs to store a large amount of heat. For instance, a wall made from PCMs could be 20 times thinner than a wall made from concrete [31]. The point when the material changes its phase greatly enhances the material's storage capacity [30], which can store a higher density of thermal energy with a smaller change in temperature [7,29], as shown in Figure 1b.



**Figure 1.** Role of PCMs application in regulating a building's indoor temperature (a) [4], and the storage capacity of materials with latent heat compared to sensible heat only (b) [32].

Generally, phase-changing in materials has four types: solid–solid, solid–liquid, solid–gas and liquid–gas [4]. However, the solid–liquid variety can be practically applied in the building sector for many reasons, including its lesser volume alteration, requiring a smaller quantity of the material to store a given amount of energy, and the nearly constant temperature by which the thermal energy is stored [4,11,33]. PCMs come in various types. Generally, they are classified into three main categories: organic PCMs, inorganic PCMs, and eutectic PCMs. Each category can be divided based on the various components of the PCMs [4,11,16,34,35], as shown in Figure 2.



**Figure 2.** Phase change materials (PCMs) categories [35].

The selection of an ideal phase change material (PCM) for the building application is important and governed by a wide range of characteristics and requirements that should be fulfilled, including thermodynamic, chemical, kinetic, and technical and economic characteristics [4,11,12,15,36]. These characteristics and requirements are summarized in Figure 3.

PCMs are integrated into building materials to enhance their thermal properties. According to Hawes [37] and Kenisarin and Mahkamov [14], building materials that can be used to host the PCMs are preferred to fulfil the following conditions:

- Being widely used in various types of structures;
- Possess a large contact surface that promotes heat transfer;
- Possess a short heat exchange depth;
- Ease of production and quality control using existing facilities;
- Their geometry and structure help them to act as the thermal conduit in exploitation and improve the function of heat reservoirs, heat exchangers and building elements;
- Ease of constructing of test structures;
- Their structure can retain the PCMs, even in the liquid state, by virtue of surface tension.

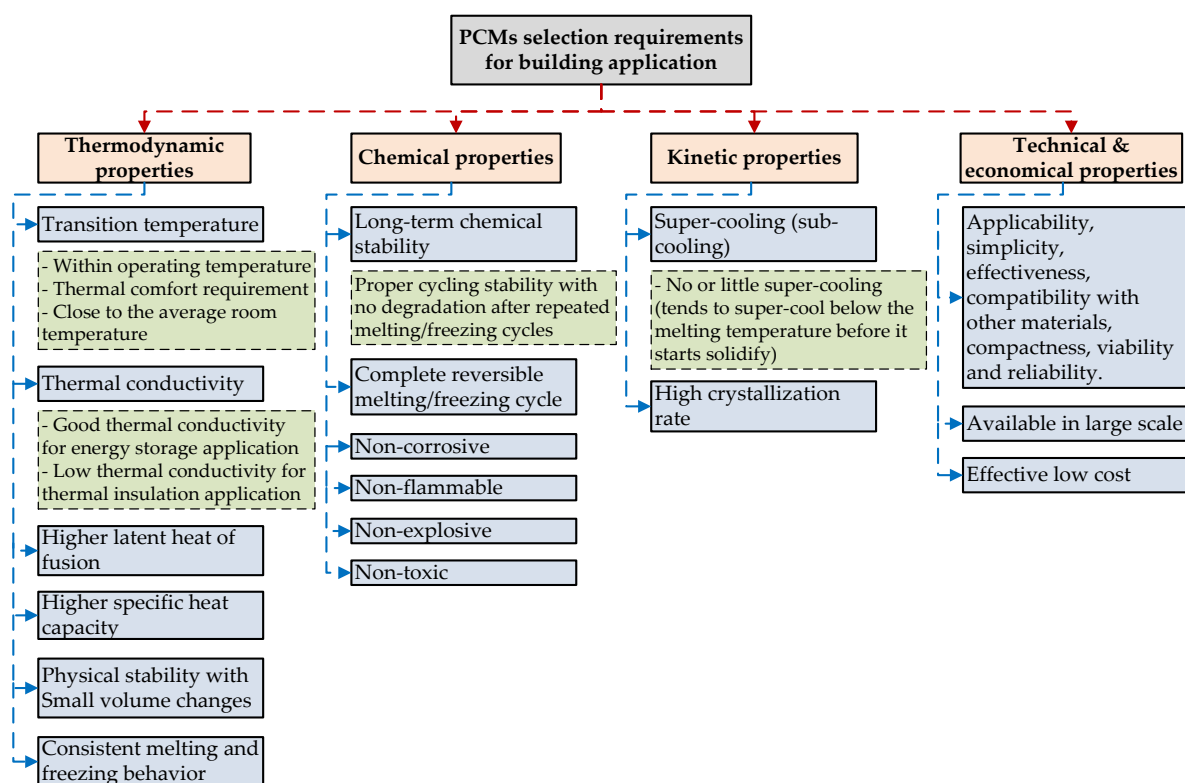


Figure 3. Selection of a PCM based on its properties.

Different technologies are available for PCMs' integration into building materials. These technologies can be classified into direct incorporation, immersion, encapsulation, and stabilization [25] (Figure 4). With direct incorporation, the PCMs are added directly into the materials, while, in immersion, the building materials and elements are immersed into the liquid PCMs allowing for absorption by capillary action. Even though both technologies are economical and practical, the leakage of PCMs, inflammability, and incompatibility with building materials are the main drawbacks of these techniques. On the other hand, the PCMs' encapsulation involves macro-encapsulation, micro-encapsulation, and nano-encapsulation. In the macro-encapsulation, PCMs are packed in different types of containers (tubes, spheres, panels, etc.), while, in the micro-encapsulation and nano-encapsulation, the PCMs particles are enclosed in a thin shell (i.e., between 1000 and 1  $\mu\text{m}$  for micro-capsules and below 1000 nm for nano-capsules) [25,38]. Finally, PCMs stabilization means that they are incorporated into a supporting porous structure such as high-density polyethylene [34].

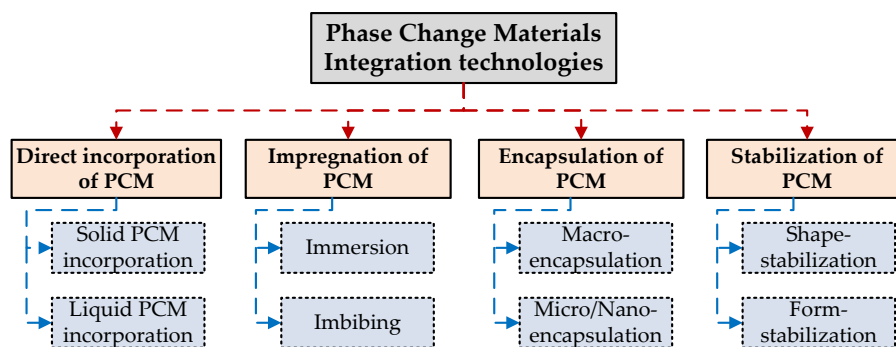


Figure 4. PCMs' integration technologies into building materials.

### 3.1. PCMs Application in Building Walls

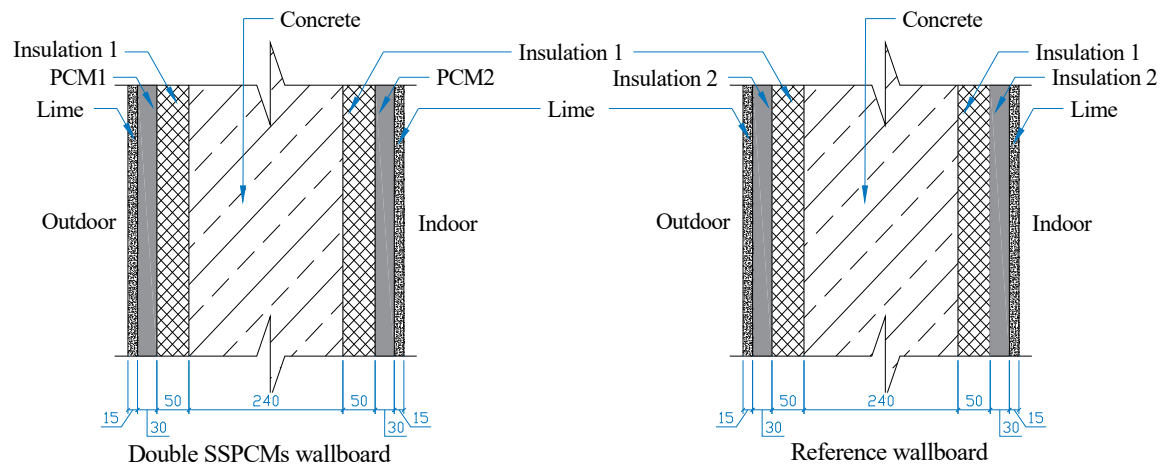
The PCMs have attracted many researchers to implement them into buildings' walls for thermal management. For instance, PCMs-enhanced bricks, blocks, wallboards, panels, and plaster were developed and tested extensively [35,39]. Generally, PCMs layers are placed close to the indoor environment [40]. For example, Ramakrishnan et al. [41] applied macro-encapsulated PCMs as the inner linings of the walls and ceilings, which effectively reduced the indoor heat stress risks and improved occupants' comfort and health. Meng, Yu, and Zhou [42] applied a composite PCMs layer made of two PCMs with different melting temperatures on the inner surface of the wall in one room to improve the wall performance in summer and winter, and the results showed better thermal performance in both seasons. Barzin et al. [6] applied PCM-impregnated gypsum boards on the internal surface of the walls and tested it with a combination of night ventilation for cooling purposes, which resulted in weekly electricity saving of 73%. Ascione et al. [43] numerically tested a 20 mm thick PCMs layer applied on the internal surface of the building external wall and achieved a reduction of 11.7% and 1.6% for summer cooling and winter heating, respectively.

PCMs layers are also placed in other positions within the buildings' walls. For example, Lei et al. [44] applied PCMs in combination with cool colours on the external surface of the walls to reduce external heat gain in tropics, in order to decrease the cooling load, and achieved 2–15% savings. Vicente and Silva [45] incorporated macro-incapsulated PCM into the centre of a brick masonry wall, which helped to reduce and delay the temperature peaks. De Gracia et al. [46] applied macro-encapsulated PCM panels inside the cavity of a ventilated façade to reduce both heating and cooling loads during winter and summer, respectively. Cao et al. [47] experimentally developed a geopolymer concrete wall containing micro-encapsulated PCM and tested it numerically, which significantly reduced the annual energy consumption for heating and cooling.

Furthermore, multiple PCMs layers were implemented in buildings' walls. However, each PCMs layer was implemented for a different purpose. For instance, Zhu et al. [48] investigated the possible energy saving achieved by the use of two layers of a shape-stabilized phase change materials-wallboard (SSPCMs) in five typical climate regions of China. Two different SSPCMs wallboards with different thermophysical properties were attached to a common concrete wall (i.e., one wallboard on the inner surface and the other on the outer surface), as shown in Figure 5. The south wall of the simulated room was integrated with the SSPCMs wallboards, while the other three walls, ceiling, and floor were thermally isolated. As an office building, the air-conditioner was set to work from 7:00 to 18:00 with a set point of 18 °C for winter and/or 26 °C for summer based on the heating and/or cooling requirements of each region.

Based on the experimental results, the external SSPCMs layer reduced external heat gain in summer. Therefore, it reduced the cooling load for the regions that require cooling, while it reduced the peak indoor temperature, leading to a more comfortable time if cooling is not required. On the other hand, the internal SSPCMs layer stored the extra indoor heat and released it back during the insufficient day-time heat in winter. Therefore, it reduced the heating load for regions that require

heating, while it improved the indoor temperature and the comfortable time in the regions that do not require heating. In addition, they noticed that the indoor temperature influenced the optimum melting temperature of the internal PCM layer, while the outdoor ambient temperature influenced the optimum melting temperature of the external PCM layer.

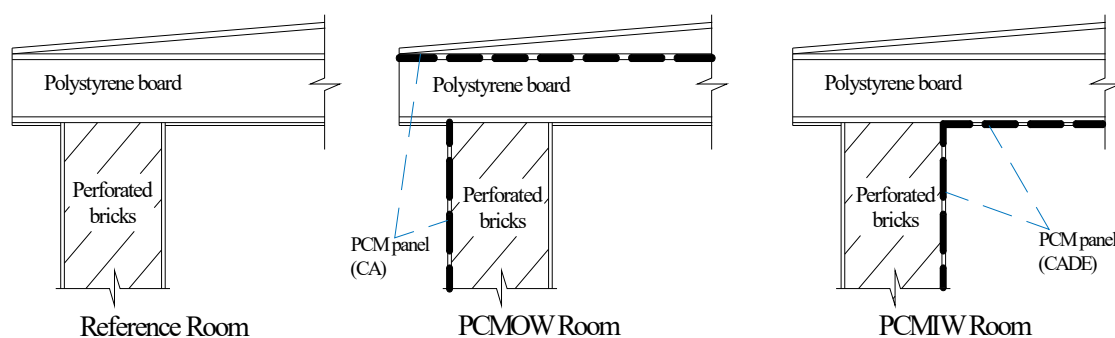


**Figure 5.** Wall with PCM layers (left) and the reference wall without PCMs (right) [48].

### 3.2. Investigation of PCMs' Optimum Position in Buildings' Walls

The PCMs' position in building walls showed various effects on the phase-change process of PCMs and, consequently, the improvement in the wall's thermal performance [40]. Therefore, some researchers investigated the effects of changing the position of the PCMs layer in building walls, looking for the optimum position of the PCMs layer.

Kong et al. [18] applied two types of macro-encapsulated PCMs on the wall's external and internal surfaces. Capric acid (CA), with a melting point of 30.2 °C, was applied on the external surface of the wall, while a mixture of capric acid and 1-dodecanol (CADE), with a melting point of 26.5 °C, was applied on the internal surface of the wall. The mixture was prepared to tackle the super-cooling effect, allowing the PCM to freeze within a small range of temperature fluctuation in the internal environment. A 240 mm thick wall, made of perforated bricks, was used to construct the walls of three rooms with the dimensions of 2000 × 2000 × 2400 mm, while the roof was constructed from an insulation sandwich board (Figure 6). One room was used as a reference without PCMs, while the other two rooms were used to install the PCM panels on the external surfaces of one room (PCMOW) and in the internal surfaces of the other room (PCMIW).



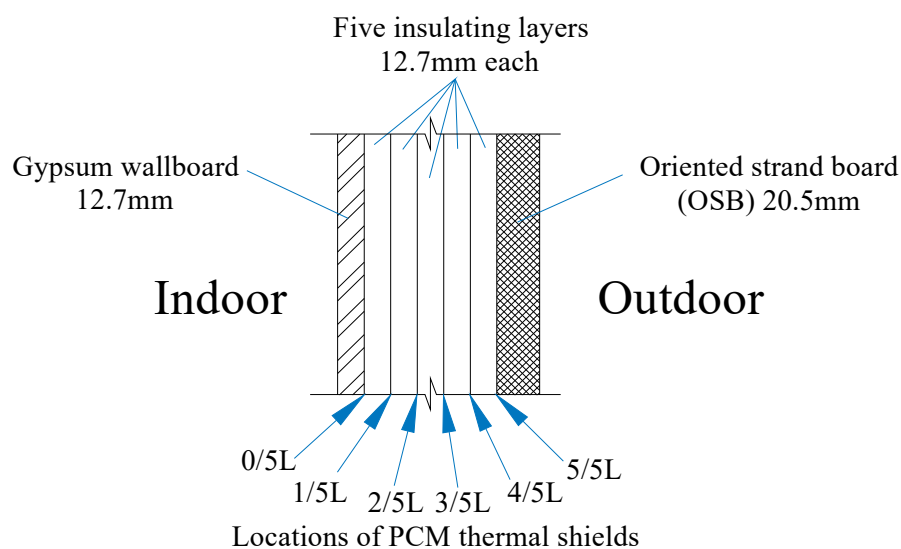
**Figure 6.** PCM layers' position in the external and internal surfaces and the reference room [18].

The experimental work involved three scenarios, including free cooling (i.e., closed doors and windows), night ventilation (i.e., opened doors and windows during the night) and night forced



ventilation (i.e., an air exhauster was installed on the window and operated during the night). The results showed that the PCM on the internal surface of the wall achieved a peak indoor temperature reduction of 2.3 °C and time delay of 3 h, compared to 1 °C and 2.1 h, respectively, for the case of PCM on the external surface. In addition, applying night ventilation and night forced ventilation further increased the reduction in the peak temperatures, especially with the PCM applied on the inner surface. This indicates the direct influence of the PCMs, which are applied on the internal surfaces, on the indoor environment. However, they mentioned that applying PCMs on the external surface of the walls has a role of thermal insulation rather than as a temperature regulator.

Jin, Medina, and Zhang [27] experimentally evaluated the thermal performance of different positions of the PCM layer in the walls to find the optimum position. A PCM thermal shield (PCMTS), with a melting temperature range of 24–34 °C, was used in this work and the experiments were performed using a dynamic wall simulator. The wall cavity was made of five insulating layers (i.e., 12.7 mm foam insulation sheet) sandwiched by a 12.7 mm gypsum wallboard for the internal surface, and 20.5 mm oriented strand board (OSB) for the external surface. The total layers of the wall without the PCMTS layer were seven layers, which allowed for six different positions of PCMTS layers to be tested. By taking the thickness of the insulation cavity as  $L$ , the tested positions from indoor to outdoor were referred to as  $0/5L$  to  $5/5L$ , as can be seen in Figure 7. In addition, one wall without PCMTS was used for control. The simulator was in an air-conditioned laboratory, with a set point of 22–24 °C which represents the indoor environment, while inside the simulator was the heat source to reflect the outdoor conditions. The heat sources in the simulator were set to produce the heat on the wall surface similar to an actual west wall and were turned ‘on’ for 11 h then turned ‘off’ for 13 h to complete one cycle of 24 h, which was repeated several times.



**Figure 7.** PCM thermal shields’ (PCMTSs’) position within the wall layers [27].

The experimental results showed that PCMTS located in  $(1/5L)$  achieved the highest reduction in the heat flux, followed by  $(0/5L)$ , with averages of 41% and 14%, respectively. They observed that as the PCMTS layer was closer to the heat source, its effect on reducing and shifting the peak heat flux was lessened. Finally, they mentioned that PCMTS in positions  $(2/5L)$ ,  $(3/5L)$ ,  $(4/5L)$ , and  $(5/5L)$  were close to the heat source which causes the complete melting of PCMs without fully solidifying. Therefore, not all the stored heat was released, which reduced the storage capacity of the PCMs. The insulating layers might also reduce the effectiveness of the internal cooling in discharging the stored heat as the PCM layer moves away. In contrast, in position  $(0/5L)$ , the PCM layer received less heat, thus its effectiveness was less. The position  $(1/5L)$  achieved the best results, since the PCM layer received heat to charge, which was enough to fully discharge.

Zwanzig, Lian, and Brehob, [23] numerically investigated a PCMs composite wallboard incorporated into different positions in a multi-layered building wall under all seasonal conditions. The multi-layered wall consisted of: (1) 9.5 mm EIFS finish (exterior), (2) 25.4 mm insulation board, (3) 12.7 mm fibreboard sheathing, (4) 89.4 mm batt insulation and (5) 15.9 mm gypsum board (interior). They used a PCM composite wallboard containing paraffin PCM with a transition temperature range of 25–27.5 °C. Three different positions for a PCM layer were considered for evaluation: Case 1, between layers 1 and 2; Case 2, between layers 3 and 4; and case 3, replacing layer 5 (Figure 8). The indoor air temperature was selected to be 20 °C for the heating season and 24 °C for the cooling season. The results showed that Case 2 achieved the best results in peak load shifting and reductions compared to other cases during both heating and cooling seasons.

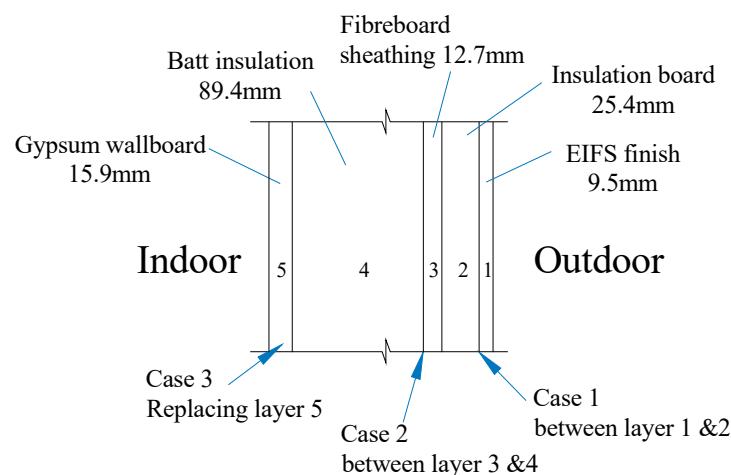


Figure 8. Positions of the PCM layer within the wall [23].

Hichem et al. [24] numerically investigated the effects of filling bricks' holes with macro-encapsulated PCMs on improving the thermal inertia of the wall. The numerical results were validated with an experimental model. After that, the effects of the PCMs type, position and amount were investigated. PCMs (i.e., five types with melting temperatures of 29.9–52 °C) were filled in the holes of the bricks in one of three positions: external, middle or internal holes (Figure 9). The results showed that the middle position achieved the highest reduction in the total heat flux (i.e., 82.1%) compared to the brick without PCMs. In addition, they increased the amount of PCMs in the bricks by filling another row of holes, which can be either the internal or external holes. The results showed that the bricks with PCMs in the middle and external holes achieved the highest reduction in the total heat flux, though the increase was only 7.92% with double the PCM quantity.

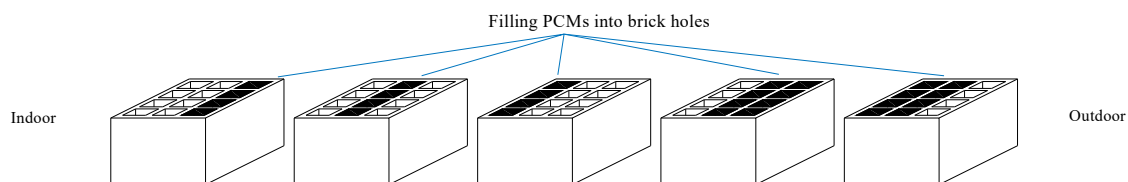
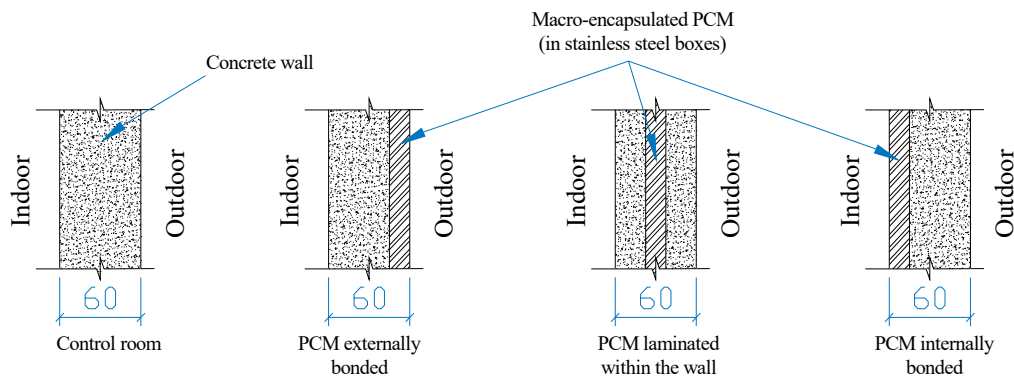


Figure 9. Filling bricks with the PCMs [24].

Shi et al. [25] experimentally investigated the effects of applying macro-encapsulated PCM in different positions within concrete walls on the indoor temperature and humidity. The PCM (i.e., paraffin with a melting temperature of 20.78 °C) was macro-encapsulated in a stainless-steel box in order to increase thermal conductivity, and was tested in three positions; (1) externally bonded, (2) laminated within the wall or (3) internally bonded (Figure 10). Three model rooms with the dimensions of 545 × 545 × 560 mm were used to test the different positions of PCM layer, while one other room,



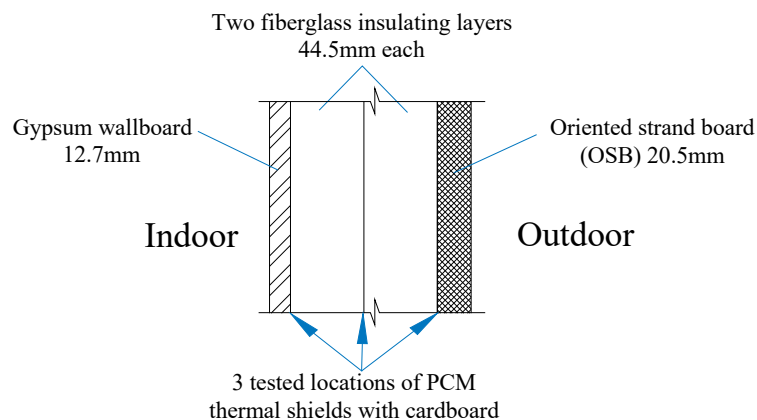
with concrete walls without PCMs, was used as a control. The total thickness of all walls in all room models was controlled to 60 mm, including all layers.



**Figure 10.** Walls description showing different positions of the PCM layer [25].

The results from the three models with PCM layers showed less fluctuation, and less and delayed maximum temperatures, compared to the control model, especially during sunny days, while the effects were limited during cloudy days. In addition, the model with PCM laminated within the wall achieved the best temperature reduction (i.e., 4 °C) amongst the three models compared to the control model, while the model with the internally bonded PCM achieved a better reduction in relative humidity (i.e., 16%). However, the authors mentioned that the three PCM models were tested on different days and for different durations and suggested carrying out the test on the same days to achieve a better comparison.

In another work, Jin, Medina, and Zhang [19] experimentally investigated the thermal performance of three different positions of PCMTS using the dynamic wall simulator. A typical North American residential wall system was selected for the test, which consists of (1) 12.7 mm gypsum wallboard, (2) cardboard, (3) PCMTS (4) two layers of 44.5 mm fiberglass insulation and (5) a 20.5 mm oriented strand board (OSB). A PCMTS layer with cardboard was placed near to the gypsum wallboard, near to the OSB and between the two insulation layers (Figure 11). The experimental setup was similar to the previous work [27]. The results showed that the higher reduction in the peak heat fluxes was 11%, with the PCMTS layer near to the gypsum wallboard within the cavity. However, the reduction in the peak heat fluxes was smaller when the PCMTS layer was placed between the two insulation layers, while there was no effect with the PCMTS layer placed within the cavity near to OSB. They concluded that PCMTS should be placed closer to the conditioned space.



**Figure 11.** Wall layers description and PCM's positions [19].

Lee et al. [26] investigated the thermal performance of building walls integrated with a thin PCMTS layer in a different position. The experiment was conducted using two  $1830 \times 1830 \times 1220$  mm identical test houses. The walls consisted of 9.5 mm plywood siding, five layers of 12.7 mm rigid foam insulation and 9.5 mm wallboards. In one test house, the PCM layer was installed in the cavity of the south and the west walls, each in one position for a total of five different positions, starting next to the wallboard (first position) and proceeding between the foam insulation layers towards the exterior side of the wall (Figure 12). The second test house was used as the control. The indoor environments of both test houses were air-conditioned.

The results showed that the PCM layer in the south wall melted only partially in Positions 1 and 2 (i.e., close to interior wall surface), while the full melting process occurred in Positions 3, 4 and 5 (i.e., close to exterior wall surface). However, the solidification process did not fully occur in Positions 3, 4 and 5. In addition, Position 3 achieved the maximum reduction in peak heat flux (i.e., 52.3%), while Position 1 achieved maximum peak heat flux delays (i.e., 6.3 h). On the other hand, for the west wall, Position 2 achieved the maximum peak heat flux reduction and maximum peak heat flux delays (i.e., 29.7% and 2.3 h, respectively). The heat flux for the west wall was higher compared to the south wall, thus the optimum PCM position moved from Position 3 in the south wall to Position 2 in the west wall (i.e., away from the heat source, to achieve a better melting/freezing cycle).

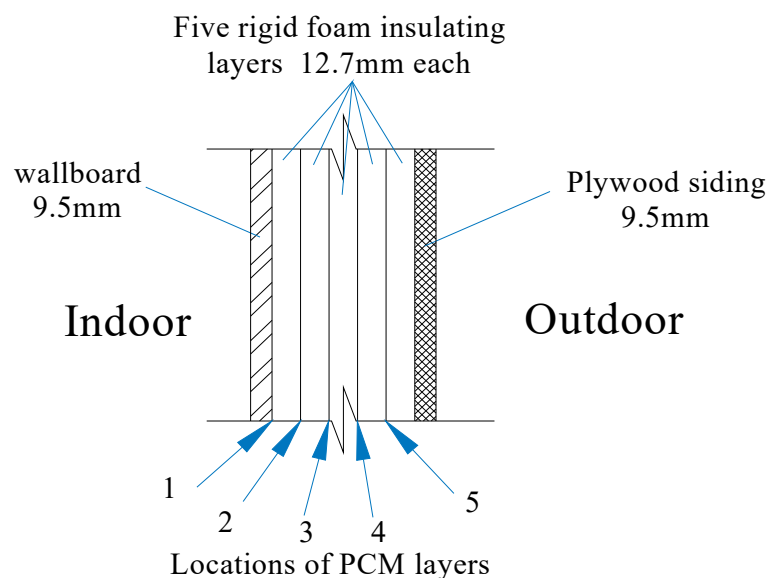


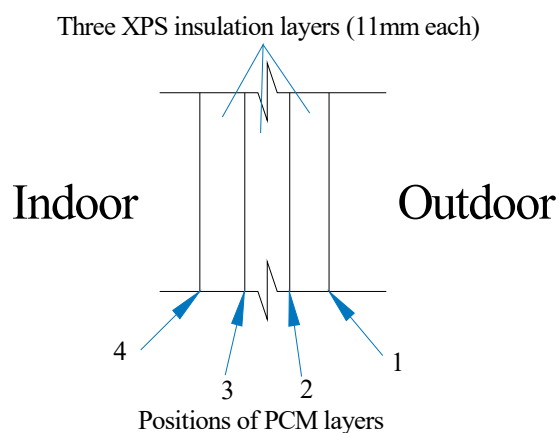
Figure 12. PCMTS position within the wall layers [26].

Lei, Yang, and Yang [21] numerically investigated the effects of applying PCMs in building envelopes on reducing the cooling load in a tropical climate. A model with dimensions of  $3000 \times 3000 \times 2800$  mm, made of 150 mm thick concrete walls, roof, and floor, was used for the simulation. A 10 mm thickness PCMs layer was used on the external surface of the wall as well as the internal surface to find the effects of the PCMs layer's position. The indoor environment was air-conditioned with a set point of 25 °C. The melting temperatures of the used PCMs were 28 and 26 °C for the external and internal layers, respectively. The results showed that the external PCM layer achieved a reduction in the peak temperature by 3–4 °C and in the yearly envelopes' heat gain by 21–32%. The PCM layer applied on the external surface achieved lower heat gain within the walls compared to the case with PCM layer on the internal surface of the wall. In addition, the daily minimum temperature was higher when PCM was applied on the internal surface of the wall, which is attributed to the heat being released to the indoor environment during the solidification process of the PCM.

In addition to their previous works, Jin et al. [40] numerically investigated the optimum position of a thin PCM layer in 16 different positions in a wall consisting of 12.7 mm internal gypsum wallboard,

89 mm insulation layer and 20.5 mm external oriented strand board (OSB). Assuming that the insulation layer thickness,  $L$ , is divided into 16 parts evenly, the PCM layer can be placed between the gypsum wallboard and the first part of the insulation layer (referred to as 0/16L), between the first and second parts of the insulation layers (1/16L), proceeding until the space between the last part of the insulation layer and the OSB (16/16L). The numerical model was experimentally validated using a dynamic wall simulator. The investigation involved examining the effects of PCM layer thickness, melting temperature and the heat of fusion and the internal surface temperature of the wall on the PCM's positions and the heat flux of the wall. The results showed the following: 1) the increased PCM layer thickness caused the optimum position of PCM to move outward, closer to the heat source (i.e., more PCM can store more heat). However, beyond a certain position, the PCM's effectiveness is reduced (i.e., it gets extra heat that keeps the PCM in the liquid state most of the time), 2) the increased PCM's melting temperature and PCM's heat of fusion caused the optimum position of PCM to move outward (i.e., closer to the outdoor heat), 3) the increased wall interior surface temperature caused the optimum position of PCM to move inward, closer to the internal environment (i.e., to get enough cooling to release the heat). However, it must be noted that the optimum position in all the investigated cases was moving between positions 1/16L and 5/16L, which means that the optimum position of the PCM layer was still in the internal part of the wall.

Fateh et al. [7] numerically and experimentally tested the PCM layer in four different positions within a lightweight wall made of XPS insulation. The control wall was made from three layers of XPS insulation with a total thickness of 33 mm. A PCM DuPont Energain® board of 5 mm thick was installed in the outer surface (Position 1), between the external and middle XPS layers (Position 2), between the internal and middle XPS layers (Position 3), or in the inner surface of the wall (Position 4), resulting in a total thickness of 38 mm (Figure 13). The wall samples were tested in an insulated test chamber between two plates. The upper plate, which was set to the main temperature of 26.5 °C and an oscillation amplitude of 12.5 °C, simulated the external temperature, while the bottom plate, which was set to 18 °C, simulated the internal temperature. Surface temperatures and heat flux were measured and showed a very good agreement with the numerical data.



**Figure 13.** PCM layer position within the XPS insulation wall layers [7].

The results showed that placing the PCM layer close to the heating source caused a larger variation in temperature. On the other hand, as the PCM layer was placed farther from the heating source and closer to the indoor environment, the XPS insulation layers reduced the temperature fluctuation, which resulted in a very low variation in PCM layer's temperatures, causing uncompleted activation of the PCM. In the studied conditions, they found that peak reduction in the thermal load was achieved in Positions 2 and 3. They concluded that integrating a PCMs layer in wall construction is influenced by the PCMs' melting temperature, climate, wall orientation, and the seasons in which the PCMs are most useful.

Gounni and El Alami [22] experimentally investigated the optimal allocation of a PCM layer in a composite wall using a reduced scale test cell, i.e.,  $400 \times 400 \times 400$  mm, to allow for more flexibility in testing several configurations of the walls. The PCM layer was a 5 mm thick flexible sheet containing composite PCM (i.e., 60% paraffin and 40% polyethylene) with a melting temperature range of 21.7–31 °C. The heating source was a controllable incandescent lamp in the centre of the testing cell representing the outdoor environment, while the test cell was located inside a conditioned laboratory kept at 15–17 °C, which represents the indoor environment. The first test involved three walls, each of 15 mm thick, made of two wood layers (control wall), 5 mm internal PCM and 10 mm external wood layers (PCM1-wall), and 10 mm internal wood and 5 mm external PCM layers (PCM2-wall). The second test involved four walls with different positions of the PCM layers. Each wall has two PCM layers and two wood layers with a total thickness of 30 mm, ordered from internal to external as follow; Wall1: wood, PCM, wood, and PCM; Wall2: PCM, wood, PCM, and wood; Wall3: two layers wood and two layers PCM; and Wall4: two layers PCM and two layers wood (Figure 14).

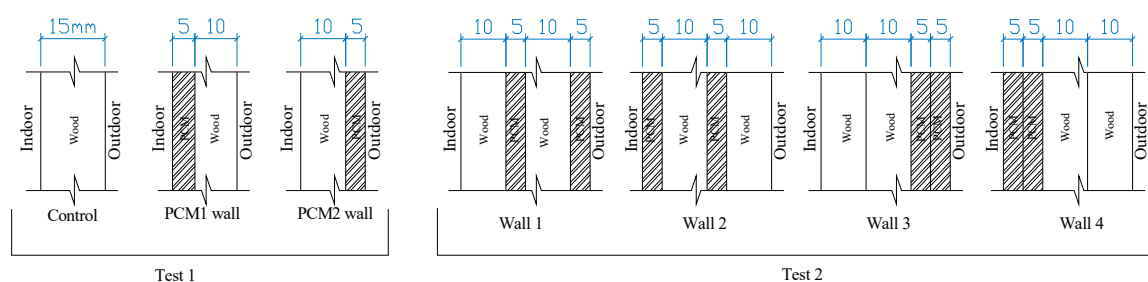
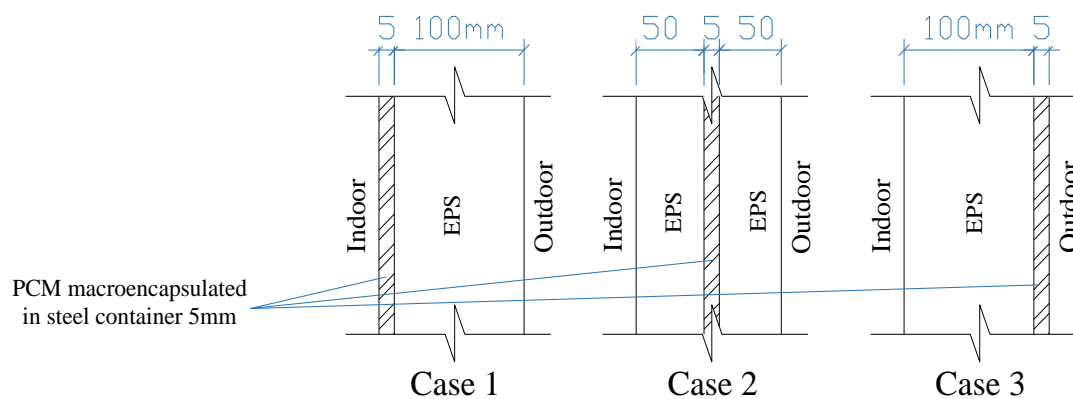


Figure 14. PCM layers' position within the wall; First test (left) and second test (right) [22].

Each test was performed for one complete cycle consists of 12 h heating, with a set point of 38 °C, followed by 12 h without heating. The results of the first test showed a time delay in temperature raising with PCM-walls compared to the control wall and the maximum reduction in the wall's internal surface temperature was achieved with PCM2-wall (i.e., PCM layer close to the heat source). They linked that to achieving complete melting of the PCM layer on the external surface of the wall compared to partial melting on the internal surface of the wall. Similar results were obtained from the second test, where Wall1 and Wall3 achieved the lowest internal surface temperatures and peak heat flux. In both walls, the PCM layers were placed towards the outdoor environment, close to the heat source. However, Wall1, which has PCM layers distributed in the wall, achieved a better performance than Wall3, which has two PCM layers placed in the external wall.

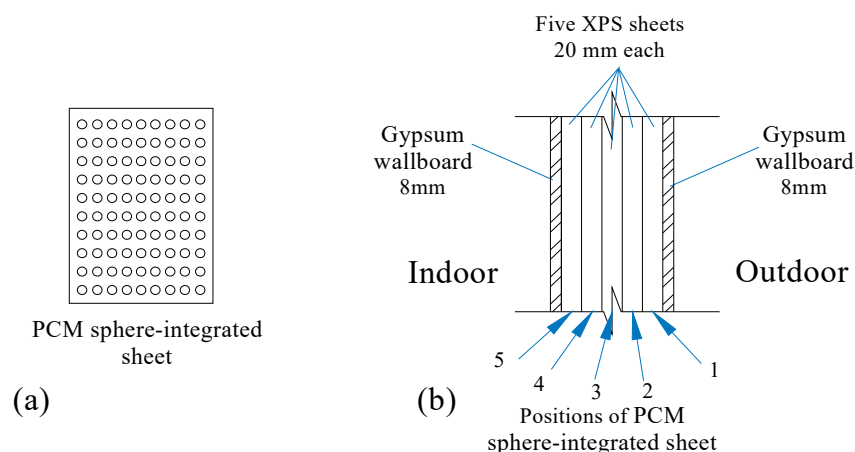
L. Zhu et al. [20] numerically investigated the influence of the position, thickness, and orientation of the PCMs layer on the indoor thermal discomfort during summer in north China. A model room, i.e.,  $2400 \times 2400 \times 2400$  mm, was used and made of 100 mm thick modular prefabricated EPS panels, covered by two 0.5 mm thick colour steel sheets on each side. An organic PCM (i.e., RT26) was placed in a  $2200 \times 2200$  mm steel container with various thicknesses inside the EPS panel. The optimum position of PCM layer, with a thickness of 5 mm, was investigated in the walls, roof, and floor in three positions; in the internal surface (Case 1), in the middle (Case 2), and in the external surface (Case 3), as shown in Figure 15. The simulation was conducted for five days (i.e., 6–10 July), using the meteorological weather data of Tianjin, and the last day was used for analysis. The simulation was validated experimentally in the outdoor environment using a modular prefabricated EPS panel with a PCM layer (i.e., RT 42 with a melting point of 42 °C) placed on the exterior surface, and the results showed good agreement. The effect of the PCM layer was numerically investigated in the six orientations.



**Figure 15.** PCM layer position within the wall's EPS layers [20].

The results showed an improvement in thermal comfort when using the PCM layer. In addition, Case 1, in which the PCM layer was placed in the internal surface of the wall, achieved better indoor air temperature reduction in most orientations (i.e., the maximum reduction of 5.07 °C was seen in the roof). However, in Case 3, in which the PCM layer was placed in the external surface of the wall, a quick phase transition process was observed, resulting in less indoor air temperature reduction (i.e., a maximum reduction of 1.80 °C was seen in the floor). In addition, they mentioned that the PCM layer in Case 3 did not absorb the heat from the indoor environment; rather, it only reduced the heat released to the indoor environment coming from outdoors. Furthermore, the authors added two indicators, namely summer overheating discomfort and cumulative discomfort duration; both indicators showed that Case 1 was the best case among the three studied positions.

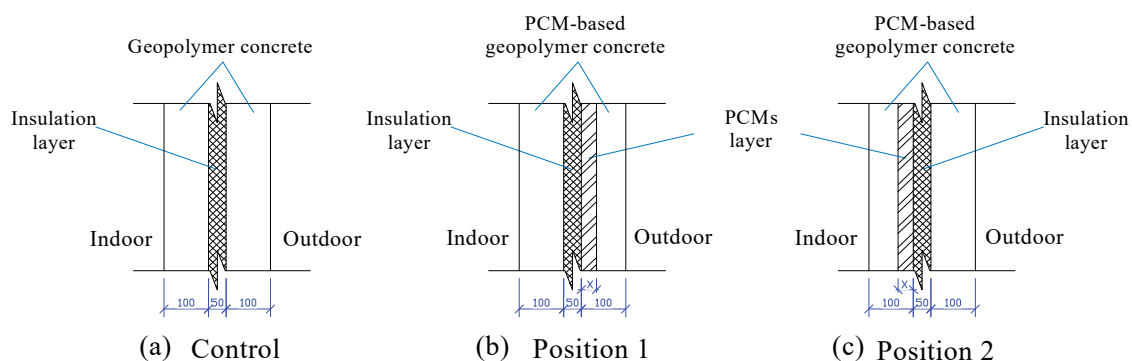
Sun et al. [49] experimentally and numerically investigated the effects of a PCM layer in five different locations in the wall for the hot summer and cold winter of Changsha, China. The control wall specimen consisted of five 20 mm thick XPS sheets and two 8 mm thick gypsum wallboards for the external and internal surfaces, forming a total thickness of 116 mm, while the width and the height were 500 and 900 mm, respectively. Paraffin-based PCM, with a transition temperature of 27–29 °C, was encapsulated in spheres made of high-density polyethylene with an external diameter of 25 mm. A total of 90 PCM spheres were integrated into one XPS sheet to produce a PCM sphere-integrated sheet, which was used to replace one layer of the five XPS sheets at a time, starting from Position 1 near the external surface and moving to Position 5 near the internal surface, (Figure 16). Three heating films, connected to voltage transformer, were placed between the external gypsum board and the first XPS sheet and used to simulate the solar radiation on the wall. The indoor air temperature was kept between 16–26 °C as the heating and cooling set points, respectively.



**Figure 16.** (a) PCM sphere-integrated sheet and (b) positions of the PCM sheet within the wall [49].

The results demonstrated that the maximum temperature reduction achieved during the summer was with the PCM-sheet in the third position, while it was in the fourth position during winter (i.e., closer to the internal surface). As heat is required during the winter, the optimum position of the PCM-sheet was moved closer to the indoor environment to benefit from the stored heat for heating. However, for the entire year, the third position was the optimum one. They stated that the optimum PCM's position is the closest one to the indoor environment, which allows for a complete phase transition of the PCM.

Cao et al. [50] numerically investigated the thermal performance of a PCM-based multi-layer wall in the climatic conditions of Oslo, Norway. The control wall was made of two 100 mm thick geopolymer concrete layers with a 50 mm thick insulation layer in between. Micro-encapsulated PCM, with a melting point of 21.9 °C, was integrated into geopolymer concrete and its thermal properties were determined in [47]. The PCM-based geopolymer concrete was used to replace the geopolymer concrete layers in the control wall to produce the PCM-based wall. In addition, a PCM layer (RT21, Rubitherm, Germany) with a melting temperature of 21 °C and various thicknesses in the range 0–50 mm was integrated within the PCM-based geopolymer concrete layers close to the insulation layer (i.e., within the external layer for Position 1 or within the internal layer for Position 2) as shown in Figure 17. The indoor environment was kept within the comfort range of 19–21 °C. The results indicated that a higher reduction in the annual energy is achieved with more PCMs additions. For instance, the reduction was 13% with the use of PCM-based geopolymer concrete layers, while it increased to a maximum of 28% with the addition of a 50 mm PCM layer. In addition, the PCM layer in Position 1, closer to the outdoor environment, has a higher energy reduction, while in Position 2 the reduction was less, which was attributed to the lower temperature variations compared to the melting range, that minimizes the PCM's performance.



**Figure 17.** (a) Geopolymer concrete wall (control), (b,c) PCM layer positions [50].

A summary of the reviewed works, ordered by the number of the investigated positions of the PCM layer, is included in Table 1.



**Table 1.** Summary of the reviewed works that addressed the optimum position of PCMs in the building's walls, ordered based on the number of investigated PCMs positions.

Author	Year	Type of Study and Period	Country and Climate	PCMs Position	PCMs Type and Properties	Indoor Environment	Findings
Kong et al. [18]	2013	Fieldwork testing (27 August 2012 to 10 September 2012)	Tianjin, China, (hot and dry summer and cold winter)	Two positions: wall's inner surface and the outer surface.	Macro-encapsulated PCMs. Two different types; capric acid for the external surface of the wall and a mixture of capric acid and 1-dodecanol for the internal surface of the wall to reduce the freezing range.	Three scenarios <ul style="list-style-type: none"> <li>• Free cooling;</li> <li>• Night ventilation;</li> <li>• Night forced ventilation.</li> </ul>	<ul style="list-style-type: none"> <li>• PCM on the inner surface of the wall achieved better peak indoor temperature reduction and time delay;</li> <li>• Night ventilation and forced ventilation further improved the performance of PCM on the inner surface of the wall;</li> <li>• PCM on the external surface of the walls have a role of thermal insulation.</li> </ul>
Zhu et al. [48]	2016	Simulation (year-round application)	China (five typical climate regions)	Two positions: wall's inner surface and the outer surface.	Double-layer shape-stabilized PCMs wallboard (SSPCM) paraffin and high-density polyethylene/expanded graphite. Two different melting temperatures for summer and winter.	Air-conditioned 7:00 to 18:00 (office building) set point 26 °C for summer and 18 °C for winter.	<ul style="list-style-type: none"> <li>• External SSPCM reduced external heat gain in summer (reduced cooling load);</li> <li>• Internal SSPCM stored the extra indoor heat in winter (reduced heating load);</li> <li>• Indoor temperature influences the optimum melting temperature of internal PCM layer, while the outdoor ambient temperature influences the optimum melting temperature of external PCM layer.</li> </ul>
Lei et al. [21]	2016	Numerical A daily and a monthly reduction	Singapore, Tropical climate	Two positions: wall's inner surface and the outer surface.	10 mm thickness PCMs layer (28 °C for outer surface and 26 °C for inner surface).	Air-conditioned (set point 25 °C).	<ul style="list-style-type: none"> <li>• The PCM applied on the external surface achieved lower heat gain within the walls;</li> <li>• The daily minimum temperature was higher when PCM were applied on the internal surface of the wall.</li> </ul>

Table 1. Cont.

Author	Year	Type of Study and Period	Country and Climate	PCMs Position	PCMs Type and Properties	Indoor Environment	Findings
Cao et al. [50]	2019	Numerical	Oslo, Norway	Two positions: 50 mm from the outer surface and 50 mm from the inner surface.	Various thicknesses 0–50 mm PCM layer (RT21, Rubitherm, Germany) with a melting temperature of 21 °C.	Air-conditioned, kept within the comfort range of (19–21 °C).	<ul style="list-style-type: none"> <li>A higher reduction in the annual energy is achieved with more PCM (using a 50 mm thick layer);</li> <li>The PCM layer closer to the outdoor environment has a higher energy reduction while the PCM layer closer to the indoor environment receives less temperature variation, which minimizes its performance.</li> </ul>
Zwanzig et al. [23]	2013	Numerical (Mathematical model) All-season	USA, Various climate zones	Three positions: internal layer, two-thirds from internal and near external layer).	PCMs composite wallboard with a melting temperature range 25–27.5 °C.	20 °C for the heating season and 24 °C for the cooling season.	<ul style="list-style-type: none"> <li>PCM layer in position two-thirds from the internal surface of the wall achieved the best results in peak load shifting and reductions during both heating and cooling seasons.</li> </ul>
Hichem et al. [24]	2013	Numerical and laboratory experiment	Algeria, Ouargla Hot arid areas	Three positions: PCMs were filled in the brick's external, middle and internal holes.	Five types of PCMs with melting temperatures varying between 29–52 °C Paraffin, and a melting temperature of 52–54 °C, was used for experimental investigation.	Internal temperature equal to 27 °C.	<ul style="list-style-type: none"> <li>The middle position achieved the highest reduction in the total heat flux;</li> <li>The addition of PCMs to external holes achieved a 7.92% improvement to the PCMs in the middle position only and was better than the addition of PCMs to internal holes.</li> </ul>
Shi et al. [25]	2014	Fieldwork testing Total of 18 days during April and May 2012	Shenzhen, China	Three positions in concrete walls: externally bonded, laminated within the wall and internally bonded.	Macro-encapsulated PCMs, paraffin in metal containers. Melting range 20.78–25.09 °C	Free running.	<ul style="list-style-type: none"> <li>Models with PCM showed less fluctuation and less and delayed maximum temperatures, especially during sunny days;</li> <li>The model with PCM laminated within the wall achieved the best thermal reduction.</li> </ul>

Table 1. Cont.

Author	Year	Type of Study and Period	Country and Climate	PCMs Position	PCMs Type and Properties	Indoor Environment	Findings
Jin et al. [19]	2014	Laboratory experiment	-	Three positions within the wall cavity: next to the internal layer, in the middle and next to the external layer.	PCMs thermal shields (PCMTSS) <i>n</i> -octadecane (organic paraffin) with a melting range 26–28 °C.	Wall simulator was located in an air-conditioned laboratory (22–24 °C).	<ul style="list-style-type: none"> <li>A higher reduction in the peak heat fluxes was achieved with the PCMTS layer near to the internal layer within the cavity;</li> <li>PCMTS should be placed closer to the conditioned space to help in the heat discharge process.</li> </ul>
L. Zhu et al. [20]	2018	Numerical and fieldwork experiment validation (five days)	North China -Tianjin	Three positions: (internal surface, in the middle and external surface).	Organic PCM, RT26 macro-encapsulated in a steel container thicknesses (2.5–5–7.5 mm).	Free running.	<ul style="list-style-type: none"> <li>The internal PCM layer achieved a better reduction in indoor air temperature and the best performance (absorbed internal and external heat);</li> <li>External PCM layer near the heating source received quick phase transition resulting in less reduction in indoor air temperature (absorbed only external heat).</li> </ul>
Fateh et al. [7]	2017	Numerical and laboratory experiment validation	-	Four positions: internal surface, an external surface, and two positions within the wall.	PCM DuPont Energain® board of 5 mm thick.	Set to 18 °C.	<ul style="list-style-type: none"> <li>The internal PCM layer did not fully activate due to XPS insulation;</li> <li>The external PCM layer caused a large variation in temperature;</li> <li>Peak reduction in the thermal load was achieved in Positions 2 and 3 (within the wall).</li> </ul>
Gounni et al. [22]	2017	Laboratory experiment (one day)	-	Four positions: internal, external, internal and before the external, and external and before the internal.	Composite PCM (60% paraffin and 40% polyethylene) in 5mm flexible sheet Melting range 21.7–31 °C.	Air-conditioned laboratory kept at (15–17 °C).	<ul style="list-style-type: none"> <li>A time delay in temperature raising was observed with PCM-walls;</li> <li>A better reduction was achieved when the PCM layer was placed in the external surface close to a heat source;</li> <li>Distributing PCM in the external and before the internal layer achieved the best performance.</li> </ul>

Table 1. Cont.

Author	Year	Type of Study and Period	Country and Climate	PCMs Position	PCMs Type and Properties	Indoor Environment	Findings
Lee et al. [26]	2015	Fieldwork testing	Lawrence, KS, USA	Five different positions within the wall cavity (Only south and west walls).	Hydrated salt-based PCMs with melting temperatures in the range of 24.79–31.36 °C.	Air-conditioned.	<ul style="list-style-type: none"> <li>Heat flux for the west wall was higher than the south wall, thus the optimum PCM position moved from Position 3 (near the middle) in the south wall to Position 2 (towards the internal) in the west wall (i.e., away from the heat source to achieve better melting/freezing cycle).</li> </ul>
Sun et al. [49]	2019	Laboratory experiment and numerical investigation	Changsha, China, Hot summer and cold winter	Five different positions within the wall (replacing one layer of the five internal XPS layers of the wall).	Paraffin-based PCM, transition temperature 27–29 °C, encapsulated in 25 mm high-density polyethylene spheres.	Float between heating (set point 16 °C) and cooling (set point 26 °C).	<ul style="list-style-type: none"> <li>Maximum temperature reduction during summer in the third position (from outdoors);</li> <li>Maximum temperature reduction during winter in the fourth position (closer to indoors to use the heat);</li> <li>The third position was optimum for the entire year;</li> <li>The optimum PCM position is the closest to the indoor environment, that allows for a complete phase transition of the PCM.</li> </ul>
Jin et al. [27]	2013	Laboratory experiment	-	Six different positions within a wall cavity (Cavity divided by 5).	PCMs thermal shields (PCMTSs) hydrated salt, with melting temperature range of 24–34 °C.	Wall simulator was located in an air-conditioned laboratory (22–24 °C).	<ul style="list-style-type: none"> <li>PCM in the second position from the internal surface achieved better performance. followed by the first position;</li> <li>PCM close to the external surface fully melted but did not fully solidify due to the heat source.</li> </ul>
Jin et al. [40]	2016	Numerical and laboratory experiment validation	-	16 different positions within the wall cavity.	Rubitherm RT27, with melting temperature 27 °C.	Air-conditioned.	<ul style="list-style-type: none"> <li>The optimum position of PCM moves towards the exterior surface of the wall with greater PCM thickness, higher melting temperatures and higher heat of fusion;</li> <li>The optimum position of PCM moves towards the interior surface of the wall with increasing wall interior surface temperature.</li> </ul>

#### 4. Discussion

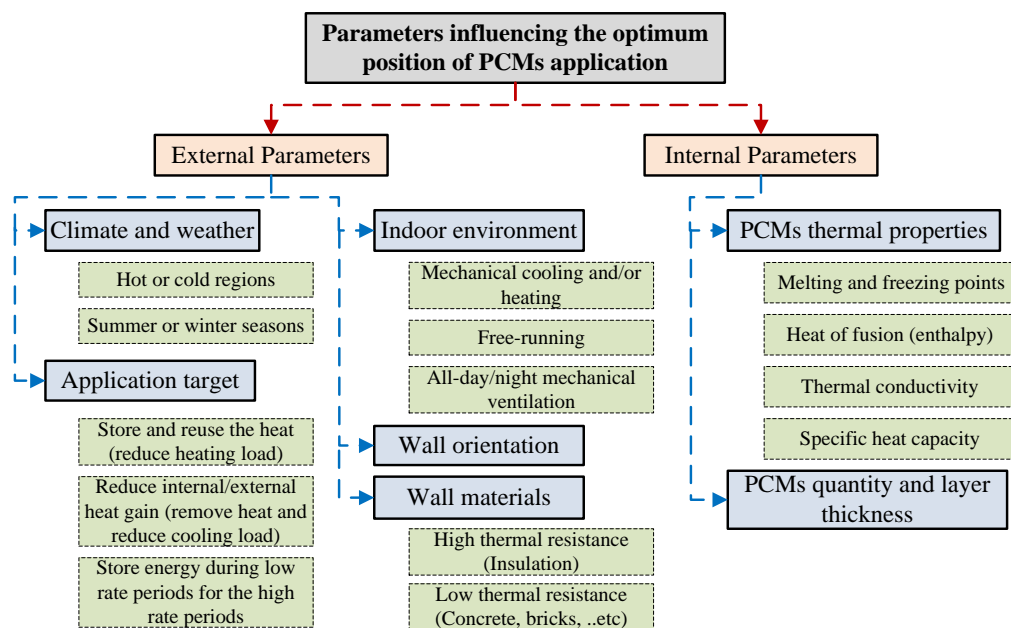
Several studies investigated the influence of the PCMs' application in different positions within building walls, with the aim of locating the optimum position. However, different results were obtained. Table 2 summarizes the obtained optimum position for the PCMs application in the reviewed works, including some of the influential parameters. To facilitate the comparison between the results, the wall was assumed to have five regions, namely the inner surface, the inner part, the middle part, the outer part, and the outer surface. Then the optimum position was transferred to the new wall from the reviewed works based on the original walls' dimensions. Based on Table 2, it can be observed that 43% of the optimum positions were obtained in the internal parts of the wall (i.e., the inner surface and the inner part) compared to 28.5% in the middle part and 28.5% in the external parts (i.e., the outer part and the outer surface). In addition, 56% of the walls, which are made of insulation materials, achieved the optimum position in the internal parts compared to 22% in the middle part and 22% in the external parts, while most of the walls, which are made of low thermally resistant materials, achieved the optimum position in the external parts. Moreover, the optimum position was achieved on the inner surface of the wall only with the free-running indoor environments.

**Table 2.** A summary of the obtained optimum position of the PCMs' application in the reviewed works, including some of the influential parameters.

Reviewed Work	Climate and (Investigated Weather Conditions)	Indoor Environment	Wall Materials	Optimum Position
Kong et al. [18]	Hot summer/cold winter (Summer)	Free running/night ventilation	Perforated bricks	Inner surface
Lei et al. [21]	Tropical (Year-round)	Mechanical cooling	Concrete	Outer surface
Cao et al. [50]	Very hot summer/mild winter (All seasons)	Mechanical cooling	Geopolymer concrete + Insulation Materials	Outer part
Zwanzig et al. [23]	Various climate zones (All seasons)	Mech. heating/cooling	Insulation Materials	Outer part
Hichem et al. [24]	Very hot summer/mild winter (Summer)	Mechanical cooling	Bricks	Middle part
Shi et al. [25]	Mild summer and winter (April)	Free-running	Concrete	Middle part
Jin et al. [19]	Fixed condition (laboratory testing)	Mechanical cooling	Insulation Materials	Inner part
L. Zhu et al. [20]	Hot summer/cold winter (Summer)	Free-running	Insulation Materials	Inner surface
Fateh et al. [7]	Fixed condition (laboratory testing)	Fixed temperature	Insulation Materials	Middle part
Gounni et al. [22]	Fixed condition (laboratory testing)	Mechanical cooling	Wood	Outer part
Lee et al. [26]	Hot summer/cold winter (Summer)	Mech. heating/cooling	Insulation Materials	Inner part
Sun et al. [49]	Hot summer/cold winter (Year-round)	Mech. heating/cooling	Insulation Materials	Middle part
Jin et al. [27]	Fixed condition (laboratory testing)	Mechanical cooling	Insulation Materials	Inner part
Jin et al. [40]	Fixed condition (laboratory testing)	Mechanical cooling	Insulation Materials	Inner part

Even though different optimum positions were obtained in the conducted studies, performing a complete daily melting/freezing cycle was a key element to achieve the best thermal performance and the optimum position of the PCMs' application. Therefore, the optimum position of the PCMs' application in the wall is the position that provides adequate heating for the PCMs to fully melt during the day-time, then adequate cooling in order for them to fully freeze during the night-time. Many parameters might influence this process and, therefore, can be categorized into two groups: external parameters and internal parameters, (Figure 18). The external parameters include climate

and weather conditions (i.e., hot or cold regions and summer or winter times), application target (i.e., reduction in indoor temperature fluctuation, storing and reuse of heat, reduction in internal heat gain, or reduction in external heat gain), indoor environment (i.e., mechanical cooling and/or heating, free-running or all-day/night mechanical ventilation), and the wall's orientation and materials. In contrast, the internal parameters include the PCMs thermal properties (i.e., melting and freezing points, enthalpy or heat of fusion, thermal conductivity, and specific heat capacity), and the PCM quantity and layer's thickness.



**Figure 18.** Main parameters that influence the optimum position of the PCM application in building walls.

Climate and weather conditions influence the PCM application target. This, in turn, affects the optimum position of PCM application. For instance, in the hot regions or during summer, the optimum position of the PCM layer is in the external part of the wall, [21,48], as the application target is to reduce the external heat gain in the indoor environment. Basically, the PCM layer absorbs the unwanted external heat, which is received by the wall, during day-time, and releases it back to the outdoor environment during night-time. In addition, the low thermal conductivity of the PCMs provides a sort of thermal insulation. However, when the PCM layer is applied in the internal part of the wall, it will release the heat back to the indoor environment during night-time, causing overheating. Nevertheless, this scenario can be used to reduce the high day-time indoor temperature if proper night ventilation is applied to remove the released heat during night-time. On the other hand, in the cold regions or during winter, the optimum position of the PCM layer is in the internal part of the wall, as the application target, in this case, is to store and reuse the heat. The internal PCM layer absorbs the heat from the outdoor environment or the produced heat in the indoor environment during day-time and releases it back to the indoor environment during night-time, which enhances the indoor thermal environment and reduces the heating load.

The indoor environment influences the freezing process of PCMs and their heat discharge. For instance, an air-conditioned indoor environment might cause the PCM layer to move away from the internal surface of the wall. The internal cooling can affect the melting process and cause partial activation of the PCM, which reduces its efficiency. Besides, if the indoor environment is not adequate to enhance the freezing process of the PCM, especially with a free running mode, the optimum position of the PCM layer will move closer to the outdoor environment, which is cooler during night-time and can enhance the freezing process, as seen in [24,25]. However, by introducing the cooler outdoor air through the night ventilation to the indoor environment, the optimum position of the PCM layer might

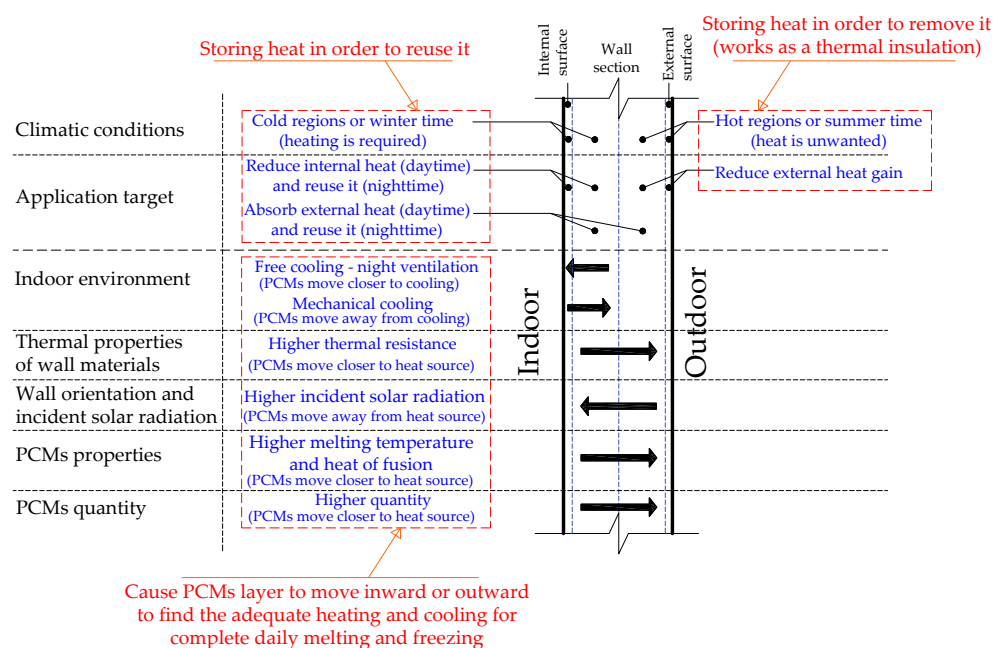


be close to the internal surface, as in [18]. Moreover, if the indoor environment has adequate heat to charge the PCM layer, the optimum position will be closer to the indoor environment, otherwise the optimum position will move outward, closer to the heat source in the outdoor environment.

The orientation and the materials of the wall can control the amount of heat received and conducted through the wall, respectively. Therefore, in both cases, the optimum position of the PCM layer might move inwards or outwards to achieve the required heating and cooling for the PCM. Depending on wall orientation, for instance, the amount of heat received by the wall and the heat flux through the wall will be different. This results in different optimum positions for each orientation, as found in [26]. On the other hand, the wall materials, (i.e., brick, concrete, lightweight materials, thermal insulation, etc.), will affect the heat conduction through the wall section due to the different thermal resistance of each material. For example, the optimum position of the PCM layer was obtained close to the indoor environment in [19,20,26,40,49], in which the walls were made of insulation layers. This might be attributed to the effect of the insulation layers on reducing the required cooling from the indoor environment for the PCM freezing process. However, the optimum position of the PCM layer will move outwards if the insulation layers of the wall caused the internal PCMs layer to not fully activate, as in [7].

Furthermore, the internal parameters have an influence similar to the influence of the wall orientation and materials. For instance, a higher PCM melting temperature influences the optimum position of the PCM layer to move outwards, closer to the heat source, to get a higher temperature that enables a complete charging process. A higher PCM heat of fusion or enthalpy, and a higher PCM quantity and layer's thickness, increases the heat storage capacity of the PCM, which influences the optimum position of the PCM layer to move outwards, close to the heat source, as well. However, beyond a specific position, the solidification process might be affected, causing a reduction in PCM performance. Therefore, based on the above discussion, the PCM layer is required to be in a position that exactly provides the required heating and cooling for the PCMs' melting and freezing processes, respectively.

Figure 19 illustrates a summary of the main findings showing the optimum position of PCMs' application in building walls based on the influences of the discussed parameters.



**Figure 19.** A summary of the main findings showing the optimum position of the PCM's application in building walls, based on several influential parameters.

Finally, selecting the optimum position of the PCMs' application in building walls can be a complicated process since it involves the influences of all the above parameters, which are connected and linked to each other, and changing any of them will affect the other parameters. Besides, it is important to mention that the optimum position of the PCMs application is not only the position that allows for the complete thermal cycle, but also the best thermal performance of the indoor environments with the lowest PCM application. Therefore, for each project, an optimization process is suggested in advance, using the available simulation tools and involving all the mentioned parameters. By doing so, the optimum position of the PCMs application, which achieves the best thermal performance, can be located.

## 5. Conclusions

Thermal energy storage (TES) and phase change materials (PCMs) are promising passive technologies that aim at improving the building materials' thermal performance and achieving thermally comfortable conditions within the indoor environment. This study reviewed TES and PCMs technologies and their application in buildings. In addition, PCMs' classification, selection requirements for building applications and integration technologies to building materials were discussed. The study also reviewed previous works, which investigated PCMs' application in building walls with a focus on the optimum position of the PCMs' application in the wall. Based on the review of the literature, it can be concluded that the optimum position of the PCMs' application in building walls can vary in different projects. The PCMs' performance efficiency is highly dependent on performing a daily complete melting/freezing cycle in order to be ready for the next cycle the following day. Otherwise, the PCMs will stay either in the solid-state or the liquid-state most of the time, causing a reduction in their performance. Therefore, the optimum position of the PCMs' application in building walls is the position at which the daily complete melting/freezing cycle can be achieved. This might be influenced by many parameters such as:

- Climate and weather conditions: in hot regions or during the summer, in which cooling is needed, PCMs application might be required closer to the outdoor environment. However, in cold regions or during the winter, in which heating is needed, PCMs application might be required closer to the indoor environment;
- Application target: reducing the external heat gain requires the PCMs to be applied towards the external surface of the wall, while reducing the internal heat gain and indoor temperature fluctuation requires the PCMs to be applied towards the internal surface of the wall;
- Indoor environment: applying free cooling, night ventilation or mechanical cooling/heating in the internal environment can affect the PCMs' solidification process, causing the optimum position to vary within the wall;
- Thermal properties of wall materials: a higher thermal resistance of wall materials can reduce the heat and coolness transfer to PCMs. This might cause the PCMs' optimum position to move outwards, closer to the heat source, or inward, closer to the conditioned indoor environment;
- Orientation and the incident solar radiation: the optimum position of PCMs within a south-facing wall might differ from the west-facing wall due to the difference in the heat received by the walls;
- PCMs properties: a higher PCM's melting temperature and a higher heat of fusion require the PCM to be closer to the heat source, i.e., closer to the external surface of the wall, up to a specific position that allows for full freezing as well;
- PCMs' quantity: a higher PCM quantity results in a higher thermal storage capacity. This will require more heat to be stored, which indicates that PCM might need to be applied near the external surface.

Therefore, for any PCMs application in building's walls, an evaluation with the help of simulation tools is suggested based on the parameters discussed above to locate the optimum position for the PCMs application.

**Author Contributions:** All authors contributed equally to this research. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Universiti Sains Malaysia, Research University Grant number (1001/PPBGN/814285).

**Acknowledgments:** The authors would like to thank the Department of Architecture, Faculty of Engineering, Sana'a University, and School of Housing, Building and Planning, Universiti Sains Malaysia for financial support.

**Conflicts of Interest:** The authors declare no conflict of interest.

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